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☞ ☞ HANDS ON ☜ ☜

☞ Building Simulation '89

The proceedings from the **Building Simulation '89** conference, held in Vancouver, B.C. last September, are available from

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Computer Science Department
California State University at Fullerton
Fullerton, CA 92634
FAX: (714) 449-7168

Cost of the proceedings is $75.00 per copy plus $3.00 s/h within the U.S.

☞ Time To Make Travel Plans

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Aug 13-17 1990 — *Electronic and Direct Digital Controls* ....
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Aug 26-Sep 1 — *ACEEE 6th Summer Study* ....
to be held at Asilomar in Pacific Grove, California. Sponsor: American Council for an Energy Efficient Economy. Contact: ACEEE 1990 Summer Study, Bldg B90H, Lawrence Berkeley Laboratory, Berkeley, CA 94720.

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Modeling Complex Daylighting With DOE-2.1C

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Daylighting is often proposed as an energy conservation strategy in new commercial buildings. This paper will describe a daylighting analysis technique using some powerful and generally unused features of the DOE-2.1C computer program in combination with scale building models and/or detailed daylighting calculations. This method was used to model and analyze various daylighting options in several new utility office buildings constructed in Oregon.

Introduction

As part of a Bonneville Power Administration field test of energy efficient commercial buildings (Energy Edge Project), extensive design assistance was provided for a number of innovative new commercial buildings in the Pacific Northwest. This design assistance included funding energy and engineering consultants and analysis. One of the program requirements was hourly building modeling to determine anticipated performance of various conservation measures. Daylighting measures were significant components of two of these buildings and posed significant analysis problems. The Oregon Department of Energy (ODOE) worked closedly with building architects, engineers, and consultants on these two projects and provided both technical assistance and building modeling.

Example Buildings Using Daylighting

These two new buildings used for analysis are both central offices of publicly owned electric utilities located in Eugene, Oregon. Both utilities are strongly committed to energy conservation. The Emerald Public Utility District (EPUD) building, as shown in Fig. 1, was designed as a state-of-the-art low energy building. The EPUD building is a two story structure with over 90% of the facility incorporating daylighting. Daylighting design features include high ceilings, perimeter light shelves, fixed louver and deciduous vine shading, high clerestory windows, diffusing cloth baffles, and low ambient target light levels. The EPUD building is constructed of heavy masonry throughout with exterior insulation, hollow concrete core floors used for night flush cooling and morning heating warmup, and indirect lighting reflected from the exposed concrete ceilings.

This article was originally published in the Proceedings of the Solar Energy Society Conference held in Denver, Colorado in June, 1989.

1. **Night-Air Flush**
2. **Conditioned Air Supply**
3. **Clerestory Windows** for deep, even daylight penetration.
4. **Core-Slab Roof** for thermal mass and night air flush.
5. **Light Shelves** are used for even daylight distribution; to provide soft, ambient indirect light; they are CRT compatible; they provide task light at each desk.
6. **Finwalls** for thermal mass, structure, and privacy.
7. **Conditioned Air Return**
8. **Core-Slab Floor** for thermal mass and night air flush.
9. **Trellises and Vines** to control summer sun.
10. **Acoustic Baffles** for sound absorption.
11. **Paired Beam** for air distribution

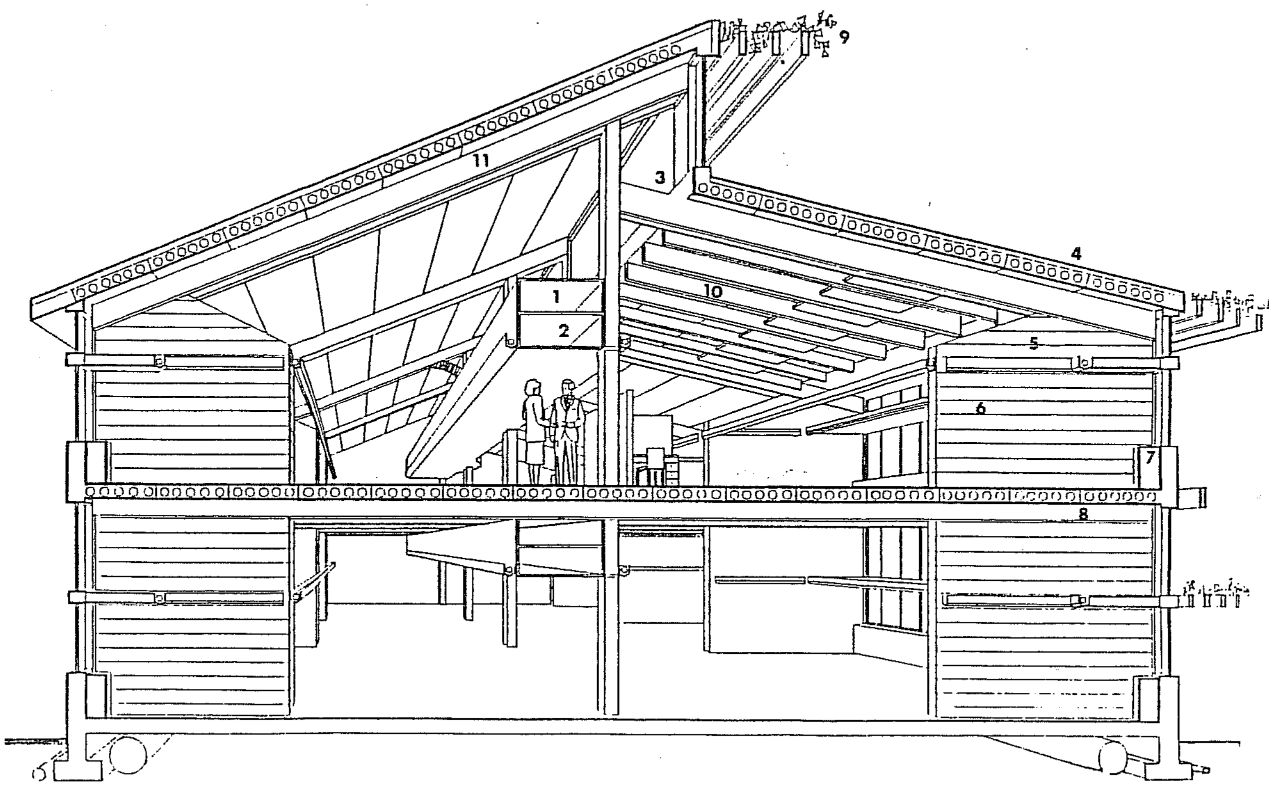
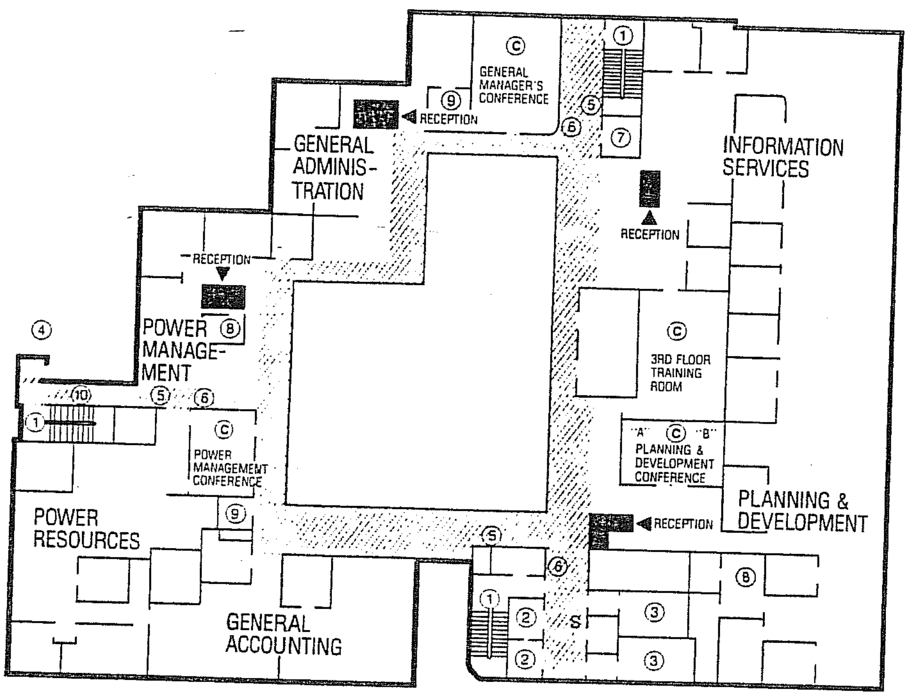


Figure 1. EPUD Building Section

The Eugene Water and Electric Board (EWEB) building is a two-building complex. The main south building is a four story office block with a central atrium with daylighting provided by north-facing sawtooth clerestory windows. The EWEB building also uses perimeter light shelves, fixed overhangs, and movable roll-down shading screens. Both the EPUD and EWEB buildings incorporate stepped dimming of light fixtures to reduce electric lighting. This is generally accomplished by turning off a bank of fluorescent bulbs in multi-lamp fixtures under computerized controls.



C Conference Rooms
1. Stairs
2. Elevators
3. Restrooms
4. Covered Outdoor Smoking Area
5. Drinking Fountain
6. Fire Ext Cabinet
7. First Aid Station
8. Copier
9. Coffee Bar
10. Bulletin Board

Figure 2. EWEB Building Plan - Third Floor

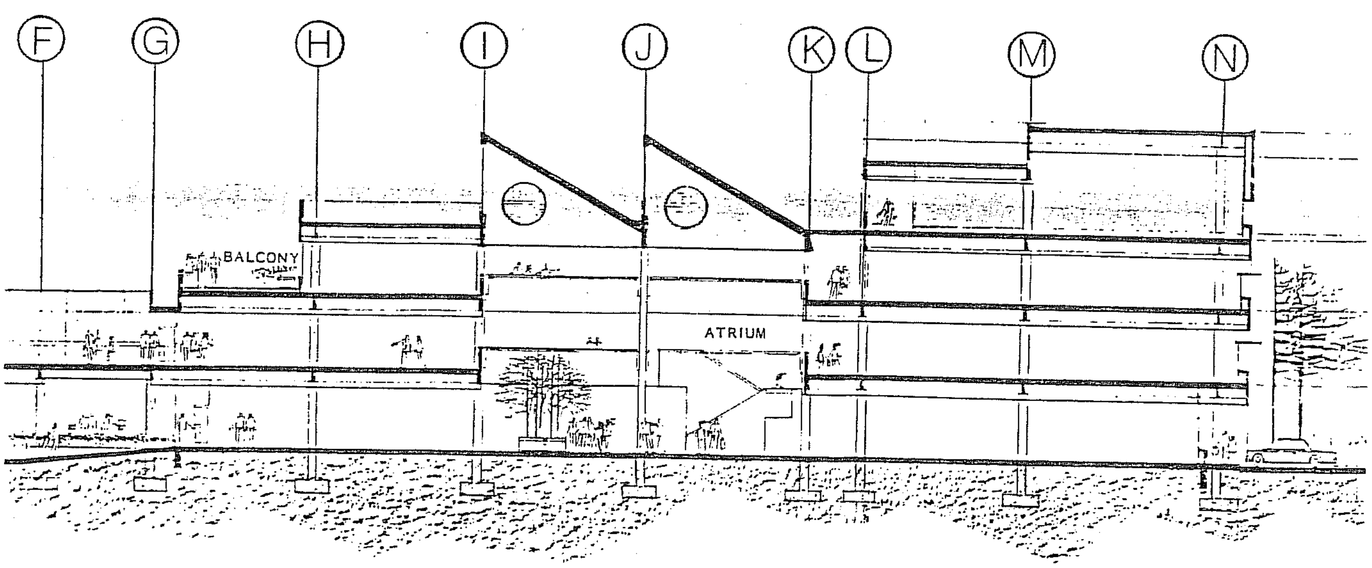


Figure 3. EWEB Building Daylighting Test Zones

Daylighting Analysis Limitations

Although DOE-2.1C supports daylighting better than most other hourly models, DOE-2 has the following limitations:

(1) daylighting is calculated accurately for only simple geometries;

(2) the daylit space must also contain the window or skylight; and

(3) complex or seasonal shading, baffles, and louvers cannot be easily analyzed.

DOE-2 and other similar computer programs can calculate daylighting in a space for simple geometries with side or top lighting. Daylighting calculations in DOE-2 use solar geometry for the direct component and the "split-flux" method for determining the internally reflected component of daylight. For internally reflected light (the dominant component in most building designs), the daylight transmitted through a side window is split into two parts--a downward flux onto the floor and walls below an imaginary window mid-plane and an upward flux onto the ceiling and walls above this imaginary mid-plane. The flux onto the ceiling is assumed to be spread evenly over the ceiling area. The floor flux is also treated the same but because of the low reflectance values generally assumed for floors, this floor flux doesn't have much impact. This split-flux method will generally not be accurate for deep spaces ($depth > 2 * height$). This method cannot accurately handle complex daylighting schemes using light shelves or reflective overhangs that are highly directional and force more light onto the ceiling.

A second and more severe limitation to daylighting analysis with DOE-2 is that the daylit space (HVAC zone) must contain the window or skylight providing the light. DOE-2 does not support light sharing from one zone to another. A commercial building might have a typical perimeter zone of depth 12 to 20 feet. Internal zones provided with daylighting shared from an adjacent perimeter zone can't be analyzed. A multi-story atrium providing daylighting to adjacent spaces poses a similar problem. Generally, even the atrium space cannot be analyzed properly. The EWEB building (Figures 2 and 3) has a four story central atrium space. For HVAC modeling, the floor zone of the atrium is a completely different comfort zone from the top space with the actual sawtooth clerestory windows and associated glazing/infiltration skin losses and gains.

Yet, the more commonly proposed daylighting strategies (light shelves, atria) fall into these problem analysis areas. Fortunately, DOE-2.1C introduced a powerful FUNCTION extension that may be used for daylighting analysis in these cases.

Using Functions in DOE-2.1C

The FUNCTIONS mechanism was added to the LOADS module in version 2.1C of DOE-2 to extended the program for complex designs not covered by the standard options built into DOE-2. The FUNCTIONS mechanism includes several features:

(1) the ability to access variables within the LOADS analysis program during the simulation;

(2) the ability to make new calculations using these LOADS variables for reporting and debugging;

(3) the option to replace certain calculated variables in the LOADS module; and

(4) a built-in interpreter supporting a pseudo-FORTRAN dialect for calculation purposes during the hourly LOADS simulation.

Using FUNCTIONS, a building modeler can replace the calculated value for certain variables in the LOADS module during the simulation based on other LOADS variables. To analyze complex daylighting, a user-defined FUNCTION can be designed to replace the DOE-2 calculated daylight values with data from either scale building models or much more sophisticated daylight illuminance calculation programs such as SUPERLITE. The technique used with the two example buildings was based on using scale building model studies.

During the design phase, scale models were constructed of sections through both buildings for daylight modeling. These scale models were tested under diffuse and clear sky conditions to determine daylight factors. The University of Oregon (Eugene, Oregon) has an artificial sky facility but it is limited to modeling diffuse sky conditions. For direct sun, the daylight factors were measured outside on clear days at various locations within the model with varying solar altitudes and azimuths. Based on these scale models, daylight FUNCTIONS were constructed for use in DOE-2. The daylight FUNCTION that was used is based on determining the interior light levels from daylighting by interpolating values based on solar altitude and azimuth. Two sample functions are outlined below.

The first example is for a simple north-facing perimeter space in the EPUD building with interior light shelves. A north-south building section is shown in Figure 1. In this case, the daylighting was approximated as a fixed daylight factor times the outside horizontal illuminance. This daylight factor was measured from scale model studies under overcast skies. The daylight factors measured under direct sun conditions were similar enough to the diffuse conditions that for simplicity, they were not used. The changes to the DOE-2 SPACE commands and the actual daylight FUNCTION used are shown in Figure 4.

A few comments would be helpful in understanding the overall scheme and DOE-2 input data semantics. The dollar sign ($) is used in DOE-2 input language as a comment delimiter. The internal DOE-2 daylighting calculations are enabled with the SPACE command DAYLIGHTING=YES. DOE-2 supports dividing an HVAC zone into two parts with separate daylight levels for each part. The size of each part of the HVAC zone with daylighting is not fixed by the program--the default is ZONE-FRACTION1 to be 1 (100% of the space). For DOE-2's internal daylight calculations, the location (LIGHT-REF-POINT) of the control point and the target light level (LIGHT-SET-POINT) in footcandles must be specified. The type of dimming system (LIGHT-CTRL-TYPE) must also be set. If stepped dimming is specified (as opposed to continuous dimming), then the number of fixed steps must be noted.

```
$ FIRST THE ADDITIONS TO THE SPACE COMMAND FOR DAYLIGHTING

1-NORTH-PER = SPACE
    .
    .  $ THE NORMAL SPACE COMMANDS
    .
DAYLIGHTING = YES
LIGHT-REF-POINT1 = (186,82,3)               $ LOCATION OF REF IN X,Y,Z
LIGHT-SET-POINT1 = 30                       $ SET PT IN FOOTCANDLES
LIGHT-CTRL-TYPE1 = STEPPED                  $ STEPPED DIMMING
LIGHT-CTRL-STEPS = 3                        $ OFF, 1, AND TWO BULBS ON
ZONE-FRACTION1 = 1                          $ ALL OF THE SPACE
DAY-ILLUM-FN = (*NONE*, MEAS-1-N-PER)       $ USER-DEFINED FUNCTION
..

$---DAYLIGHTING FUNCTION FOR NORTH SPACE WITH LIGHT SHELF
    FUNCTION
    NAME = MEAS-1-N-PER
    LEVEL = SPACE ..

$ FIRST WE ASSIGNED THE LOADS VARIABLES WE WILL USE IN THE CALCULATIONS.
$ FOR CONVENIENCE, USE THE SAME NAMES BUT LIMIT TO SIX CHARACTER NAMES,
$ THE LIMIT OF PSEUDO-FORTRAN

ASSIGN   OHISKF = OHISKF                    $ HORIZONTAL ILLUMINANCE FROM
                                            $    OVERCAST PART OF SKY
         CHISKF = CHISKF                    $ HORIZONTAL ILLUMINANCE FROM
                                            $    CLEAR PART OF SKY
         HISUNF = HISUNF                    $ HORIZONTAL ILLUMINANCE FROM SUN
         ILLUM1 = DAYLIGHT-ILLUM1 ..        $ DAYLIGHT ILLUMINANCE
                                            $  AT REF. PT 1 (FOOTCANDLES)

CALCULATE   .. $ NOTE: NEXT TWO LINES MUST BEGIN IN COLUMN 7
      ILLUM1 = .80*(HISUNF+CHISKF+OHISKF)*0.036
      END
END-FUNCTION ..
----+----1----+----2----+----3----+----4----+----5----+----6----+----7
```

Note that 0.036 is the measured daylight factor from the scale model for overcast conditions. The .80 value adjusts the measured model data for losses in visible light transmission through double glazing.

Figure 4. EPUD User-Defined Daylight Function for North Perimeter

The daylighting function to be used in a zone (SPACE) is set with the DAY–ILLUM–FN command. DAY–ILLUM–FN is a special DOE-2 function which determines the hourly daylight illuminance and glare index at each reference point in a space. The command takes the name of a user-defined function to be called before the internal DOE-2 daylight calculations and a function to be called after DOE-2's own calculations. The special name *NONE* is an internal name for not calling a function. In our case, we insert a function to be called after the DOE-2 internal calculations so we can replace certain daylighting loads values. The same daylighting function can therefore be used by several similar zones. Although this scheme provides a great deal of flexibility, the DOE-2 internal calculations will be performed even if all their associated output values are replaced.

The actual FUNCTION to be invoked must be defined later in the input data deck after all of the other LOADS information. The current DOE-2 implementation supports up to 100 user-defined functions. A function is delimited by the FUNCTION and END–FUNCTION statement. The FUNCTION command has three parts:

(1) name and use information;

(2) an assignment section for assigning names of variables used from the simulation; and

(3) a calculation section supporting a pseudo-FORTRAN interpreter.

The function NAME assigned will be how a particular function is referenced in the DOE-2 LOADS input data. The LEVEL refers to at what "level" of the simulation this particular function applies. Functions are contained within the hourly loop of the DOE-2 simulation. Functions can apply at the entire building (BUILDING or BLDG) level, the HVAC zone (SPACE) level, or at the component level (EXTERIOR–WALL, UNDERGROUND–WALL, WINDOW, or DOOR). In our example with LEVEL = SPACE, the function would be performed within the hourly space calculation loop of the DOE-2 simulation.

Variables used within a user-defined function are declared through the use of the ASSIGN command. These local variables or table variables are limited to 1-7 character names chosen by the user (pseudo-FORTRAN). In our example, the local variables have generally been assigned the same name as the DOE-2 LOADS variable they store. The CALCULATE section begins the actual pseudo-FORTRAN statements that will be interpreted at runtime. Clearly, simulation times will increase with the number and complexity of FUNCTIONS used since these are interpreted. The typical speed of an interpreted versus compiled section of code is usually one to two orders of magnitude (10 to 100 times) slower.

The second example (Figure 5) is the more useful case illustrating daylighting affected by solar altitude. This function was used for a south-facing interior zone in the EWEB building receiving light shared from an adjacent perimeter zone with light-shelves. A sample building section is shown in Figure 3. This case illustrates using a daylighting FUNCTION based on interpolating from a table for determining the daylighting factor from solar altitude. The daylight function uses a pseudo-FORTRAN function PWL(table,value).

```
$---DAYLIGHTING FUNCTION FOR INTERIOR SOUTH SPACE
    FUNCTION
    NAME = MEAS-2-SOUTH
    LEVEL = SPACE  ..

$ ASSIGN LOCAL VARIABLES USED

ASSIGN          PHSUND = PHSUND                 $ SOLAR ALTITUDE IN DEGREES
                OHISKF = OHISKF                 $ HORIZONTAL ILLUMINANCE FROM
                                                $   OVERCAST PART OF SKY
                CHISKF = CHISKF                 $ HORIZONTAL ILLUMINANCE FROM
                                                $   CLEAR PART OF SKY
                HISUNF = HISUNF                 $ HORIZONTAL ILLUMINANCE FROM
                                                $    SUN
                ILLUM1 = DAYLIGHT-ILLUM1        $ DAYLIGHT ILLUMINANCE
                                                $  AT REF. PT.1 (FOOTCANDLES)

$ NOW OUR TABLE OF ALTITUDE AND DAYLIGHT FACTORS FROM SCALE MODEL
    CLDF1 = TABLE (0,.04) (10,.038) (45, .001) (70,.055) ..
CALCULATE   .. $ NOTE: NEXT THREE LINES MUST BEGIN IN COLUMN 7
      IDIRH = HISUNF + CHISKF       $ CLEAR SKY ILLUMINANCE
      ILLUM1 = .80*(PWL(CLDF1,PHSUND)*IDIRH + OHISKF*.019)
      END
END-FUNCTION ..
----+----1----+----2----+----3----+----4----+----5----+----6----+----7
```

Note that 0.019 is the measured daylight factor from the scale model for overcast conditions. The CLDF1 (clear day factor) tables values are from measurements at various solar altitudes. The .80 value adjusts the measured data for losses in visible light transmission through double glazing.

Figure 5. EWEB User-Defined Daylight Function for North Perimeter

In DOE-2, PWL is a built-in utility function that does a piecewise linear interpolation from a table based on the value. This routine is very useful in DOE user-defined functions providing a simple mechanism to interpolate data from a table. Writing equivalent pseudo-FORTRAN code in a user-defined function will run much more slowly, since it would be interpreted. Unfortunately, no equivalent function is available to interpolate from a two dimensional table. Such a feature would be ideal for daylighting calculations. The most general user-defined function would interpolate from a table of daylight factors based on altitude and azimuth. A two dimensional interpolation must be written in pseudo-FORTRAN and interpreted at runtime.

It is interesting to note that this technique is in fact the mechanism used internally by DOE-2 to calculate the daylighting available at any hour. Before the start of the simulation, a table of daylight factors for a window are calculated based on solar altitude and azimuth. The hourly space loop uses these precalculated tables for interpolation at simulation runtime.

Note that the DOE-2 SPACE definition in our second example contains a "dummy" window of small size. One limitation of the FUNCTION mechanism as currently implemented in DOE-2 is that a normal DOE-2 (internal) daylighting calculation must be performed to be able to use the FUNCTION. Therefore, a window (in this case a small dummy) must exist in the SPACE for DOE-2's default calculations to work. I have suggested to LBL a mechanism to disable the internal calculations if they are to be replaced anyway by a FUNCTION value. Hopefully, this feature will be added in a future revision.

Results and Conclusions

Our experience using his method for analyzing complex daylighting has been successful. Reports available from the DOE-2 simulation provide useful monthly summaries for the percent of lighting energy reduction, average daylight illuminance, hours lighting above setpoint, and glare information. Another report also depicts a summary of energy reduction by hour of day versus month. Using this information, the building designer can make better informed decisions on the daylight features such as window sizes and floor to ceiling heights and their impact on estimated energy savings. For example, the window sizes below the light shelves in the EPUD building were significantly reduced based on the results of scale models and DOE-2 simulations. The orientation of the sawtooth clerestories in the EWEB building were changed from south to north-facing.

One of the major drawbacks in using these techniques is the cost (time and dollars) of the scale building models for daylighting studies. The cost of each building model and measurement study was several thousand dollars. Although this can become a considerable expense on a small design process, these models have also proved useful in providing qualitative feedback to the design team on daylight issues. The limitation to these models is that they are not easily changed. If the scale measurements and DOE-2 results indicate that ceiling heights can be lowered, this can become a costly model change to get revised daylight factors. The ideal scheme might use an initial scale model in conjunction with some second or third generation daylight analysis program like SUPERLITE to calculate daylight factors for small changes.

Both of these buildings are being monitored over a three year period. In addition, detailed building audits are being conducted every 6 months to capture schedule information and note changes or problems with equipment. From the preliminary data collected thus far, this analysis method is most limited by the actual controls installed and operated in these buildings. Although the lighting controls in both buildings were considered reasonable state-of-the-art when bid, they should be considered primitive by microcomputer standards.

Acknowledgements

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